ASTROPHYSICS OF THE SOFT GAMMA REPEATERS AND ANOMALOUS X-RAY PULSARS

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I summarize the recent advances in our understanding of the Soft Gamma Repeaters: in particular their spin behavior, persistent emission and hyper-Eddington outbursts. The giant flares on 5 March 1979 and 27 August 1998 provide compelling physical evidence for magnetic fields stronger than $10\,B_{QED} = 4.4\times10^{14}$ G, consistent with the rapid spindown detected in two of these sources. The persistent X-ray emission and variable spindown of the 6-12 s Anomalous X-ray Pulsars are compared and contrasted with those of the SGRs, and the case made for a close connection between the two types of sources. Their collective properties point to the existence of *magnetars*: neutron stars in which a decaying magnetic field (rather than accretion or rotation) is the dominant source of energy for radiative and particle emissions. Observational tests of the magnetar model are outlined, along with current ideas about the trigger of SGR outbursts, new evidence for the trapped fireball model, and the influence of QED processes on X-ray spectra and lightcurves. A critical examination is made of coherent radio emission from bursting strong-field neutron stars. I conclude with an overview of the genetic connection between neutron star magnetism and the violent fluid motions in a collapsing supernova core.

1. Introduction

During the last 30 years, a comfortable picture of the Galactic neutron star population emerged: neutron stars are born with largely dipolar magnetic fields of $\sim 10^{11} - 10^{13}$ G, which do not decay significantly unless the star accretes upwards of $\sim 0.1\,M_\odot$ from a binary companion. This picture is based on observations of neutron stars whose pulsed emissions are powered either by rotation, or by accretion. In the first case, there are strong selection effects against observing radio pulsations from a star whose dipole magnetic field is much stronger than the quantum electrodynamic value $B_{QED} = m_e^2 c^3/e\hbar = 4.4 \times 10^{13}$ G. At a fixed age, the spin period $P \propto B_{dipole}$ – after the magnetic dipole torque has pushed P well above its initial value – and the spindown luminosity $I\Omega\dot{\Omega} \propto B_{dipole}^{-2}$. The radio pulsations are also expected to be beamed into an increasingly narrow solid angle, a dramatic example being the 'new' 8.5 s PSR J2144-3933 (Young, Manchester, & Johnston 1999). The upper envelope of the distribution of measured pulsar dipole fields has, nonetheless, increased significantly with the recent discovery of PSRs J1119-6127 and J1814-1744, the second of which is inferred to have a polar field in excess of 10^{14} G (Camilo et al. 2000). The apparent paucity of neutron stars with $B_{dipole} > B_{QED}$ in accreting systems places tighter constraints on their birth rate *if* they have the same distribution of natal kicks as ordinary radio pulsars.

Although strong by terrestrial standards, a $\sim 10^{12}$ G magnetic field is, in a dynamical sense, quite weak. It contributes only $\sim 10^{-9}$ of the hydrostatic pressure (when the effects of proton superconductivity in the stellar core are taken into account). Much stronger magnetic fields can be generated by vigorous convective motions in a supernova core, $B \sim 10^{15}$ G (Thompson & Duncan 1993, hereafter TD93). Substantial evidence has accumulated in recent years[1] for neutron stars whose much stronger magnetic fields ($B_{dipole} \sim 10\, B_{QED} = 4.4 \times 10^{14}$ G) decay significantly on a very short timescale ($\sim 10^4$ yr). These *magnetars* were predicted to spin down much more rapidly than ordinary radio pulsars, and should be elusive (although not necessarily impossible to detect) as pulsed radio sources. They have been most cogently associated (Duncan & Thompson 1992, hereafter DT92; Paczyński 1992; Thompson & Duncan 1995, hereafter TD95) with the Soft Gamma Repeaters: a small peculiar class of neutron stars that emit extremely luminous and hard X-ray and gamma-ray bursts. The growing group of Anomalous X-ray Pulsars (Mereghetti 2000) may be closely related (Thompson & Duncan 1996, hereafter TD96).

The defining property of a magnetar is that its decaying magnetic field outstrips its rotation as a source of energy for X-ray and particle emission — by some two orders of magnitude if the core field is as strong as $\sim 10^2\, B_{QED}$ (TD96). The observational signatures of this decay include persistent X-ray and particle emissions and, if $B > (4\pi\theta_{max}\mu)^{1/2} = 2 \times 10^{14}\, (\theta_{max}/10^{-3})^{1/2}$

[1]Due to the very unfortunate absence of Jan van Paradijs and Chryssa Kouveliotou, this review covers the phenomenology of the Soft Gamma Repeaters and Anomalous X-ray Pulsars, as well as theoretical aspects of strong-field neutron stars. It combines two recent summaries of the bursting behavior of the SGRs (Thompson 2000b) and the persistent emission and spindown of the SGRs and AXPs (Thompson 2000c). See Norris et al. (1991) for a review of the early literature on the SGRs, and Frail (1998) and Mereghetti (2000) for a more complete review of radio-silent neutron stars and the AXPs.

G, sudden outbursts triggered by fractures of the rigid crust. (Here μ is the shear modulus and θ_{max} the yield strain in the deep crust.)

2. Soft Gamma Repeaters

The SGRs are best known for two giant flares on March 5, 1979 and August 27, 1998 (from SGR 0526-66 and SGR 1900+14 respectively). These remarkable bursts, separated by almost 20 years, are nearly carbon copies of each other. They released $\sim 4 \times 10^{44}$ and $\sim 1 \times 10^{44}$ erg in X-rays respectively (Cline 1982; Hurley et al. 1999a; Feroci et al. 1999; Mazets et al. 1999b and references therein) and had very similar and striking morphologies. Each was initiated by a short and intense ($t \sim 0.2 - 0.5$ s) spike. The luminosity of this spike exceeded the classical Eddington luminosity – above which the outward force due to electron scattering exceeds the attractive force of gravity: $L_{edd} \simeq 2 \times 10^{38}$ erg s^{-1} for a $1.4\,M_\odot$ neutron star – by a factor $3 \times 10^6 - 10^7$ in the case of the March 5 event (Fenimore, Klebesadel, & Laros 1996). The ensuing softer emission, which lasted $200 - 400$ s and radiated somewhat more energy, had a much more stable temperature even though its luminosity exceeded $\sim 10^4\,L_{edd}$. In the March 5 flare, this tail had a striking 8-second periodicity of a very large amplitude, which was inferred to be the rotation period of SGR 0526-66. The August 27 event exhibited a similar 5.16 s periodicity of an even larger amplitude.

These SGRs are more generally characterized by short (~ 0.1 s) X-ray outbursts with luminosities as high as $10^4\,L_{edd}$. The statistics of the these short bursts have some intriguing similarities with earthquakes and Solar flares (Cheng et al. 1996). According to the most recent analyses, the bursts of SGR 1806-20 (Göğüş et al. 1999b) and SGR 1900+14 (Göğüş et al. 1999a) have a power-law distribution of energies $dN/dE \propto E^{-1.6}$ that extends over some 4-5 decades. The distribution of waiting times is lognormal, peaking at ~ 1 day (Hurley et al. 1996; Göğüş et al. 1999a,b). In the case of SGR 1806-20, continuous monitoring in 1983 showed that the burst fluence accumulates in a piecewise-linear manner while the source is active (Palmer 1999). This indicates the existence of multiple active regions, internal to the star.

The four known SGRs are also persistent X-ray sources of luminosity $10^{35} - 10^{36}$ erg s^{-1} (Rothschild, Kulkarni, & Lingenfelter 1994; Murakami et al. 1994; Hurley et al. 1999b; Woods et al. 1999b). Although the time average of the bursting emission is uncertain due to the intermittency of SGR activity, it is in order of magnitude comparable to the persistent output. Periodicites have been convincingly detected in two sources: $P = 7.47$ s for SGR 1806-20 (Kouveliotou et al. 1998); and $P = 5.16$ s for SGR 1900+14 (Hurley et al. 1999c). This measurement of the spin preceded the August 27 event in the case of SGR 1900+14, and agreed with the periodicity detected in the giant outburst. This narrow clustering of persistent luminosities and especially of spin periods in the SGR sources provides an important clue to the energy source that powers them.

Evidence that SGR 0526-66 is a young neutron star comes from its positional coincidence with a supernova remnant N49 (age $\sim 7 \times 10^3$ yr) in the LMC. If the star has been spun down by a vacuum magnetic dipole torque to a period of 8 s, then one infers a polar dipole field of 6×10^{14} $(t/10^4 \text{ yr})^{-1/2}$ G (Duncan & Thompson 1992). Additional evidence that the SGRs are young neutron stars comes from the association of the other three – with varying degrees of certainty – with supernova remnants (Kulkarni & Frail 1993; Vasisht et al. 1994; Hurley et al. 1999b; Woods et al. 1999b) or regions of massive star formation (Fuchs et al. 1999).

An important observational breakthrough, which supports this interpretation, came with the recent detection of rapid spindown in SGRs 1806-20 and 1900+14. Both sources have (coincidentally) nearly the same characteristic age of $P/\dot{P} = 3000$ yr (Kouveliotou et al. 1998, 1999; Marsden, Rothschild, & Lingenfelter 1999; Woods et al. 1999c; Woods et al. 2000). The inferred polar magnetic field strength exceeds 10^{15} G in both cases, in the simplest model of an orthogonal vacuum rotator. Deviations from this torque behavior are outlined in §5.2.

3. Anomalous X-ray Pulsars

The Anomalous X-ray Pulsars constitute a separate group of a half-dozen neutron stars that have been detected through their persistent X-ray pulsations but have not (yet) been observed to burst (Mereghetti & Stella 1995; Duncan & Thompson 1995; Van Paradijs, Taam, & Van den Heuvel 1995; Mereghetti 2000). The AXPs share with the SGRs remarkably similiar persistent X-ray luminosities ($L_X \sim 3 \times 10^{34} - 10^{36}$ erg s^{-1}), spin periods ($P \sim 6 - 12$ s), and characteristic ages ($P/\dot{P} \sim 10^3 - 10^5$ yr). They are all consistently spinning down. At least three are associated with young supernova remnants.

This overlap between the SGRs and AXPs in a *three*-dimensional parameter space would be surprising if the two classes of sources were powered by fundamentally different energy sources. Accretion has been suggested for the AXPs – either in a low mass X-ray binary (Mereghetti & Stella 1995) or through a fossil disk (Van Paradijs et al. 1995). In that case, one infers $B_{dipole} \sim 10^{11} - 10^{12}$ G. However, the need for an active energy source in the SGRs, almost certainly involving a strong magnetic field, combined with the variability of the X-ray output of some AXPs, led to the suggestion that the AXPs were also powered by a decaying magnetic field, and were spinning down essentially by a vacuum magnetic dipole torque (TD96; Kouveliotou et al. 1998). In that case, the estimated dipole fields rise to $\sim 10^{14} - 10^{15}$ G. The possibility remains that some AXPs are strongly magnetized but otherwise passively cooling neutron stars (Heyl & Hernquist 1997a,b). The SGRs are highly intermittent as burst sources (activity in SGR 0526-66 was only detected during the years 1979 to 1983); this provides a hint that some AXPs have experienced X-ray outbursts in the past and will burst in the future. Combining both classes of sources, one roughly estimates the net birth rate of SGRs/AXPs as $\sim 1 \times 10^{-3}$ per year (Thompson et al. 2000a, hereafter T00).

The identification of AXPs with inactive magnetars resolves some of the problems associated with accretion models. There is no evidence for binarity in any of these sources (Kaspi, Chakrabarty, & Steinberger 1999; Mereghetti 2000). If their X-ray emission were powered by accretion from a low-mass binary companion, then the long orbital evolution time – $10^7 - 10^8$ yr due to gravity wave emission – combined with the presence of a few AXPs inside SNR of age $\sim 10^4$ yr would imply far more sources in the Galaxy than are in fact observed (TD96). The fossil disk model appears to be on firmer grounds, and is testable by searches for optical/UV emission reprocessed by the disk from the central X-ray continuum. (See Perna, Hernquist, & Narayan 2000 for detailed modelling.) The X-ray spectra of the AXPs are peculiarly soft by the standards of X-ray binaries, which suggests that if they are accreting then their magnetic fields are weaker than 10^{12} G. Fields that weak can barely provide the spindown torque measured in the AXPs 1E 1048.1+5937 and 1E 1841-045 (Li 1999).

Interest in the connection between the AXPs and radio pulsars has been raised by the recent discovery of PSR J1814-1744, which is positioned near the AXP 1E 2259+586 in the $P - \dot{P}$ plane (Camilo et al. 2000). It should first be noted that the spindown age of 1E 2259+586 ($P/2\dot{P} \sim 2 \times 10^5$ yr) is > 10 times the age of the supernova remnant CTB 109 near whose center it sits. Since all the other AXPs and SGRs for which this comparison can be made have *shorter* spindown ages, it seems likely that the spindown torque of 1E 2259+586 has decayed, and that over most of its history this AXP sat a factor of ~ 10 higher in the $P - \dot{P}$ plane. Several effects – alignment, field decay, or a previous phase of accelerated spindown – could explain this observation in the magnetar model (T00).

The strong-field pulsar J1814-1744 is not a conspicuous X-ray source, being at least 10-100 times weaker than the AXPs (Pivovaroff, Kaspi, & Camilo 2000). More generally, there appears to be a bifurcation in the level of internally-generated dissipation between the SGRs (and AXPs) and radio pulsars of a similarly young age. A critical parameter which could explain this bifurcation is provided by the internal (e.g. toroidal) magnetic field

(TD96). Above a flux density of $\sim 100\, B_{QED}$ – corresponding to 5-10 times the dipole fields inferred from spindown – there is a rapid increase in the rate of ambipolar diffusion through the degenerate core (see also §7).

4. SGR Outbursts: Physical Diagnostics

The strength of the magnetic field is probably the most important parameter to be determined in the SGR and AXP sources. In this section, we review how the extreme properties of SGR outbursts directly point to flux densities higher than $10\, B_{QED} = 4.4 \times 10^{14}$ G in these sources.

4.1. TRIGGER AND ENERGETICS OF SGR BURSTS

To power one giant flare like the March 5 and August 27 events, an SGR must be able to store $\sim 10^{45}$ erg of potential energy. This should be compared with the maximum elastic energy $\sim 10^{44}\, (\theta_{max}/10^{-2})^2$ erg that can be stored by the crust of a neutron star whose yield strain is θ_{max}. It should be emphasized at this point that a magnetic field stressing the outer Coulomb lattice of the star actually contains more available energy ($\delta B^2/4\pi$) than is stored by the lattice itself ($\sim \frac{1}{2}\theta^2\mu$ where μ is the shear modulus). The ratio is $\sim 4\pi\mu/B^2 = 10^2\, (B/10\, B_{QED})^{-2}$. Nonetheless, even with this amplification it is not possible for a star composed of *strange quark matter* to retain enough potential magnetic energy to power the March 5 and August 27 giant flares. The elastic energy of its crust is smaller than that of a neutron star by at least four orders of magnitude (Alcock et al. 1986).

Why are the giant flares so rare, when short SGR bursts are relatively common? Why is there a gap of more than two orders of magnitude in fluence? One possible explanation is that the giant flares involve a large propagating fracture in the neutron star crust, whereas the short bursts require only a localized yield of the crustal lattice (TD95). A large scale motion of the crust is highly constrained compared with, e.g., a metal sheet, because the crust floats stably on the neutron star core and is very nearly incompressible. For this reason, a large fracture requires the collective and simultaneous motion of many smaller units. It is interesting to note, in this regard, that some earthquake models based on cellular automata show a bimodal distribution of events, with a secondary peak at the highest energies (Carlson, Langer, & Shaw 1994).

How precisely is energy injected into the magnetosphere of the neutron star? The very fast ($\sim$ ms) rise times both of some short SGR bursts (Kouveliotou et al. 1987) and the giant outbursts (Fenimore et al. 1996; Hurley et al. 1999a; Mazets et al. 1999b) point to a localized and direct injection of energy. Indeed, much of the energy that is eventually radiated in the burst may have been injected on a much shorter timescale than the measured duration of the X-ray pulse. Direct evidence for this behavior comes from the intense initial spikes of the March 5 and August 27 events, which released a few tens of percent of the net outburst energy over $\sim 10^{-3}$ of the duration.

A magnetic field $B > (4\pi\theta_{max}\mu)^{1/2} \sim 2\times 10^{14}\,(\theta_{max}/10^{-3})^{1/2}$ G can fracture the crust, but is far too weak to induce anything but a horizontal motion. As a result, energy is injected in the magnetosphere, in two distinct regions. The motion will, in general, have a rotational component that creates tangential discontinuities in the magnetic field. A disturbance of the magnetosphere propagates at the speed of light, which is some 300 times the shear wave velocity c_μ in the deep crust. Thus, reconnection occurs rapidly, and induces transverse Alfvén waves of frequency $\sim c/R_{NS}$ on the connecting closed loops of magnetic flux. These waves can dissipate effectively by cascading to high wavenumber through non-linear interactions (Thompson & Blaes 1998). Because they are current-carrying, a minimal density of electrically charged particles is required to support them, which in the giant flares implies a significant optical depth to scattering across the magnetosphere. The current density (and optical depth) rises as the cascade moves to higher wavenumber, where it is finally damped by Compton drag off the electrostatically heated pairs. When the rate of transfer of wave energy exceeds a critical level $10^{42}\,(\ell/10$ km) erg s^{-1} within a volume ℓ^3, no stable equilibrium between heating and radiative cooling is possible. The plasma runs away to a dense, hot fireball which cools diffusively on a much longer timescale (TD95; Thompson et al. 2000b).

The second dissipative region lies much farther out in the magnetosphere. The crustal motion (on a horizontal scale ℓ) can be expected to excite shear waves of frequency $\nu \sim c_\mu/\ell$, which in turn couple to magnetospheric Alfvén modes at a radius $R_\nu \sim c/3\nu \sim 100\,\ell$. This outer excitation may dominate if (for example) the fracture is buried deep in the crust, and has been identified with two bursts from SGR 1900+14 whose hard spectra resemble those of cosmological GRBs (Woods et al. 1999d).

4.2. FRACTURING VS. PLASTIC CREEP

Can the magnetar model accomodate two classes of sources with widely different bursting behavior, but similar levels of internally-generated dissipation? If the magnetic field in the deep crust exceeds $B_\mu \equiv (4\pi\mu)^{1/2} \sim 6\times 10^{15}$ G, lattice stresses are not able to compensate a departure from magnetostatic equilibrium, and the crust must deform plastically (TD96). Indeed, the internal flux density above which the magnetic field is transported through the neutron star core on a timescale of $\sim 10^4$ yr lies close to this value (TD96; Heyl & Kulkarni 1998). This suggests that a magnetar is capable of two dissipative modes: one dominated by brittle fracturing and bright X-ray outbursts, and a second dominated by plastic creep. These two modes correspond naturally to the SGRs and to the Anomalous X-ray Pulsars. In principle, both modes can operate simultaneously in the same star if its magnetic field is inhomogeneous.

4.3. HARD SPIKES OF THE MARCH 5 AND AUGUST 27 EVENTS

The initial spikes of the two giant outbursts had all the appearance of an expanding $e^{\pm}$ fireball carrying $\sim 10^{44}$ erg. (In the case of the March 5 event, $L \sim 3 \times 10^6 - 10^7\ L_{edd}$ and $T \sim 500$ keV: Mazets et al. 1999b; Fenimore et al. 1996.) The peak luminosity is intermediate, on a logarithmic scale, between that of a thermonuclear X-ray flash and the bright γ-ray fireballs that are observed at cosmological distances. If the fireball contained comparable energy in radiation and in the rest energy of (baryonic) matter, then its duration could be expressed in terms of the radius $R(\tau_{es} = 1) \geq (E\sigma_T/4\pi m_p c^2)^{1/2}$ of the scattering photosphere as $\Delta t \sim R(\tau_{es} = 1)/c \sim 2(E/10^{44}\ \mathrm{erg})^{1/2}$ s, about 10 times the observed value. We conclude that the initial fireball must have in fact expanded relativistically, and was powered by a very clean energy source.

The most obvious candidate is a magnetic field that experiences a sudden rearrangement. On energetic grounds, the (external) magnetic field must exceed $\sim 10B_{QED}$ to power $\sim 10^2$ giant outbursts over $\sim 10^4$ yr. One might consider a hybrid model in which the energy is initially released inside the neutron star, in the form of crustal shear waves or torsional Alfven waves in the liquid core. As we now show, fields of comparable strength are required to transmit this energy to the magnetosphere. The large output of the giant outbursts requires a large scale for this energy release, and hence a low frequency for the excited mode. For example, a fracture of dimension $\ell \sim 1$ km (a conservative lower bound) will excite a shear wave of frequency $\nu \sim 10^3\ (\ell/1\ \mathrm{km})^{-1}$ Hz. The resulting harmonic displacement ξ of the crust will in turn excite oscillations of the dipolar magnetic field lines at a radius $R_\nu \sim c/3\nu \sim 10^7\ (\nu/\mathrm{kHz})^{-1}$ cm. Because only a narrow bundle of the outer field is excited, the outward wave luminosity is a steep function of ξ, $dE_{wave}/dt \simeq \frac{1}{2}B_{dipole}^2 R_{NS}^2 c\,(2\pi\xi\nu/c)^{8/3}$, or

$$\frac{dE_{wave}}{dt} \simeq 2 \times 10^{44} \left(\frac{B_{dipole}}{10\,B_{QED}}\right)^2 \left(\frac{\xi}{0.1\ \mathrm{km}}\right)^{8/3} \left(\frac{\nu}{10^3\ \mathrm{Hz}}\right)^{8/3} \qquad \mathrm{erg\ s^{-1}}, \tag{1}$$

(Thompson & Blaes 1998). For example, an elastic distortion of the crust of energy $\sim 10^{44}$ erg corresponds to $\xi \sim 10^{-2}\,R_{NS} \sim 0.1$ km, and the luminosity approaches $10^7\,L_{edd}$ only if $B_{dipole} \sim 10^{15}\,(\nu/10^3\,\mathrm{Hz})^{-4/3}$ G!

Nonetheless, the short $\sim 0.2 - 0.5$ s duration of the initial hard spikes of the March 5 and August 27 outbursts provides direct evidence that internal (rather than external) magnetic stresses trigger these giant outbursts. A 10^{15} G magnetic field will move the core material at a speed $\sim B/\sqrt{4\pi\rho}$ through a distance 10 km in that period of time. By contrast, the fireball resulting from a sudden unwinding of the external field would last only $\sim R_{NS}/c \sim 10^{-4}$ s (TD95).

4.4. OSCILLATORY TAILS OF THE MARCH 5 AND AUGUST 27 EVENTS

After the initial hard spike, each of the two giant outbursts released an even greater amount of energy in an extended oscillatory tail. The temperature during this phase was much more stable in spite of the hyper-Eddington flux, $L/L_{edd} \sim 10^4$ (e.g. Mazets et al. 1999b). These observations suggest that a significant fraction of the initial burst of energy was trapped on closed magnetic field lines, which implies a strong lower bound to the surface dipole magnetic field, $B_{dipole} > 2 \times 10^{14}\,(E_{fireball}/10^{44}\ \mathrm{erg})^{1/2}(\Delta R/10\ \mathrm{km})^{-3/2}$ $[(1\ +\ \Delta R/R_{NS})/2]^3$ G (TD95; Hurley et al. 1999a).

The density of this trapped energy is so high that it must form a thermal fireball, composed of $e^{\pm}$ pairs and γ-rays, at a very high temperature of ~ 1 MeV. The optical depth to scattering across this plasma bubble is huge, approaching $\sim 10^{10}$. It is clear that the plasma cannot cool by simple radiative diffusion from its center: that would take $\sim 10^3 - 10^4$ times the observed burst duration. The bubble cools instead as a sharp temperature gradient develops just inside its outer boundary, and this boundary propagates inward as a cooling wave (TD95). If the magnetic field is predominantly dipolar, then the radiative flux across the field is concentrated near the surface of the star: the opacity of the E-mode scales as $B^{-2} \propto R^6$. A cylindrical bundle of field lines containing relativistic plasma therefore has a radiative area (and luminosity) that decreases linearly with time, as is observed in a number of short SGR bursts (e.g. Mazets et al. 1999a). If higher multipoles dominate the near magnetic field, then the opacity will be much more uniform over the surface of the fireball. Parametrizing the radiative area in terms of the *remaining* fireball energy as $A \propto E_{fireball}^{\alpha}$, the luminosity works out to

$$L_X(t) = L_X(0)\left(1 - \frac{t}{t_{evap}}\right)^{\alpha/(1-\alpha)}. \tag{2}$$

Here t_{evap} is the time at which the cooling wave propagates to the center of the fireball and the fireball evaporates. This analytic law provides an excellent fit to extended lightcurve of the August 27 event for $\alpha \sim 0.7$ (Feroci et al. 2000).

The fireball temperature inferred for the short SGR bursts is lower if the confining volume is as large as in the giant flares ($T \sim 100$ keV for an energy $\sim 10^{41}$ erg). However, a recent analysis of the August 29 burst from SGR 1900+14 (which appears to have been an aftershock of the August 29 giant flare) points to an active region covering only ~ 0.1 percent of the neutron star surface (Ibrahim et al. 2000). This is consistent with a strong localization of the injected energy, leading to the formation of a fireball with a similar temperature of ~ 1 MeV.

4.5. QED PROCESSES: RADIATIVE AND SPECTRAL IMPLICATIONS

The transport of X-ray photons through a very strong (super-QED) magnetic field is determined by two coupled processes: Compton scattering and photon splitting $\gamma \rightarrow \gamma + \gamma$ (and merging $\gamma + \gamma \rightarrow \gamma$) (TD95). Even at very large scattering depth, the dielectric properties of the medium are dominated by vacuum polarization in the intense magnetic field. The normal modes of the electromagnetic field are then linearly polarized (e.g. Mészáros 1992) with $\delta\mathbf{E} \perp \mathbf{B}_0$ in one case (the extraordinary or E-mode) and $\delta\mathbf{B} \perp \mathbf{B}_0$ in the other (the ordinary mode or O-mode).

The E-mode splits because, in this situation, its energy and momentum can be conserved by dividing it into two obliquely propagating O-mode photons. (Or, at a lower rate, into a pair of E-mode and O-mode photons.) The O-mode is *not* able to split because its energy and momentum cannot be so conserved.[2] In a vacuum, neither mode is able to split for the simple reason that the two daughter photons must remain colinear to conserve energy and momentum, and there is no phase space for the process. In marked contrast with the strong B^6 scaling of the splitting rate in sub-QED magnetic fields, the splitting rate approaches a B-independent value in fields much stronger than B_{QED}, $\Gamma_{sp}(\omega, B, \theta_{kB}) = (\alpha_{em}^3/2160\pi^2)\,(m_ec^2/\hbar)\,(\hbar\omega/m_ec^2)^5 \sin^6\theta_{kB}$ (Adler 1971; Thompson & Duncan 1992). Here, $\alpha_{em} \simeq 1/137$ and θ_{kB} is the angle between the photon's wavevector and the background magnetic field. This implies immediately that a E-mode photon propagating a distance $R_{NS} \sim 10$ km through a super-QED B-field will split if $\hbar\omega > 38\,(R_{NS}/10\text{ km})^{-1/5}$ keV (TD95; Baring 1995).

[2]These selection rules depend essentially on the inequality $n_O > n_E$ between the indices of refraction of the two modes. Note that both n_O and n_E depart only very slightly from unity even in magnetic fields as strong as $\sim 10^{16}$ G. The inequality is reversed, $n_E > n_O$, when plasma dominates the dielectric properties of the medium; but in such a situation the particle density is enormous and the photons will in practice follow a Planckian distribution. The problem of calculating the emergent spectra of SGR bursts focusses on much lower temperatures and densities where departures from local thermodynamic equilibrium can occur.

Compton scattering becomes strongly anisotropic in a background magnetic field, with a strongly frequency-dependent cross-section (Mészáros 1992). In contrast with a dense plasma, both vacuum modes interact resonantly with an electron (or positron) at the Landau frequencies. Near the surface of the star, the energy of the first Landau excitation [$\simeq (2B/B_{QED})^{1/2} m_e c^2$ when $B \gg B_{QED}$] is much higher than the temperature of the emerging X-radiation. In this situation, there is a strong suppression of the E-mode's scattering cross-section, $\sigma_E = (\omega m_e c/eB_0)^2\,\sigma_T$, but not of the O-mode's (e.g. Herold 1979). This suppression greatly increases the radiative flux close to the neutron star – both from its surface (Paczyński 1992, Ulmer 1994) and across the confining magnetic field lines of a trapped fireball (TD95).

However, even in the region where the E-mode is able to stream freely, the O-mode with its large cross section can still undergo many Compton scatterings and relax to a Bose-Einstein distribution. Given the strong frequency dependence of the splitting rate, there is clearly a critical temperature above which the distributions of the E- and O-modes both become thermal, which works out to $T_{sp} = 11\,(R_{NS}/10\text{ km})^{-1/5}$ keV (TD95). This value agrees well with the best fit black body temperature of the oscillatory tail in the August 27 giant flare (Feroci et al. 2000). (The term 'photon-splitting cascade' appearing in some of the recent literature is a misnomer. *If the Compton depth is high enough to convert the O-mode back to the E-mode and allow more than one generation of splitting, then X-rays are redistributed in frequency mainly by the Compton recoil.*)

The sharply peaked sub-pulses within the oscillatory tails of the March 5 and August 27 events have a simple interpretation in the magnetar model, and are consistent with the presence of a trapped fireball (TD95). This pattern requires a collimated, quasi-hydrodynamical outflow of the X-radiation. In an intense magnetic field, the rapid rise of the E-mode opacity with radius provides a mechanism for self-collimation: if baryonic matter is suspended in the magnetosphere by the hyper-Eddington radiative flux, then E-radiation will escape by pushing this matter to the side. In addition, a significant fraction of the E-mode flux near the E-mode photosphere is converted to the O-mode by scattering and by photon splitting (Miller 1995; TD95). The O-mode flows hydrodynamically along the magnetic field even in the presence of a tiny amount of matter, $\dot{M}c^2/L_O \sim (GM_{NS}/R_{NS}c^2)^{-1}(L_O/L_{edd})^{-1}$. Further collimation occurs if the photosphere is aligned with extended (dipolar) magnetic field lines.

Scattering at the electron cyclotron resonance can probably be neglected during outbursts from a magnetar: the resonance sits at a large radius $8\,R_{NS}\ (B_{dipole}/10\,B_{QED})^{1/3}\ (\hbar\omega/10\,\text{keV})^{-1/3}$, where the outflowing photons are sufficiently collimated to suppress the resonant scattering depth below unity. Scattering at the ion cyclotron resonance has a significant optical depth τ_{ion} if electrons and ions dominate the *electron*-scattering opacity: it is $\tau_{ion} \sim (\pi/4\alpha_{em})n_e\sigma_T R(B/B_{QED})^{-1}$ in a dipolar magnetic field. An important effect is to convert photons between the E- and O-modes and to increase significantly the opacity of the E-mode at low frequencies. (This may be relevant to the < 7 keV suppression of the radiative flux found by Ulmer et al. 1993 in the bursts of SGR 1806-20.)

4.6. PREDICTIONS OF THE MAGNETAR MODEL

Here we mention three direct observational diagnostics of magnetars.

1) Afterglow radiation from the heated surface that is exposed to a high temperature fireball. The surface absorbs $\sim 10^{-3} - 10^{-2}$ of the fireball energy before it dissipates. This heat will be re-released on a timescale comparable to or longer than the observed duration of the SGR outubrst. The resulting luminosity increases monotonically with B, and is $\sim 10^{39} \times$ [exposed area/(10 km)^2] erg s^{-1} for $T_{fireball} \sim 1$ MeV and $B \sim 10\,B_{QED}$ (TD95). Direct evidence for afterglow at this level is present in a ~ 4 s burst from SGR 1900+14 that followed the August 27 flare by less than 2 days (Ibrahim et al. 2000).

2) Absorption or emission in the persistent emission at the ion cyclotron resonance $\hbar\omega = 2.8\,(Z/A)(B/10\ B_{QED})$ keV. A direct measurement of the surface magnetic field would be provided by the simultaneous identification of a spin-flip transition: the two frequencies are very nearly degenerate for electrons, but differ by a factor 2.8 for protons. This measurement is probably more feasible in the AXPs, whose persistent emission has a much smaller non-thermal component than the SGRs.

3) Little or no reprocessing of X-rays into the IR/optical/UV bands by an orbiting disk. The persistent X-rays of the SGRs and AXPs do not, in the magnetar model, result from accretion. Only a modest amount of material can be placed in orbit around the neutron star through hyper-Eddington winds. Detailed calculations of reprocessing in the fossil disk model for the AXPs have been performed by Perna, Hernquist, & Narayan (2000) (see also Chatterjee, Hernquist, & Narayan 2000). It is hard to avoid reprocessing $\sim 10^{-2}$ of the central X-ray source $L_X \sim 10^2\, L_\odot$ in this model.

5. Variable Spindown of the SGRs and AXPs

The four known SGRs are persistent X-ray sources, and in two cases persistent periodicites have been detected: $P = 7.47$ s for SGR 1806-20 (Kouveliotou et al. 1998); and $P = 5.16$ s for SGR 1900+14 (Hurley et al. 1999c). Together with the 8-s periodicity of the March 5 event and the 6-12 s spin periods of the AXPs, these values are clustered in a remarkably narrow range.

5.1. SPINDOWN AGES

In the magnetar model, the long spin periods of the SGRs were ascribed to large torques driven by magnetic dipole radiation (DT92), possibly amplified by a persistent flux of Alfvén waves and particles (Thompson & Blaes 1998). A key motivation for this model came from the early association between the March 5 burster and the supernova remnant N49 in the LMC (Cline 1982, and references therein): the 8-s periodicity corresponds to a magnetic dipole field of 6×10^{14} G (polar) at an age of $\sim 10^4$ yr. Of all the SGR and AXP sources, the spindown of the AXP 1841-045 is most consistent with simple magnetic dipole radiation (Gotthelf et al. 1999): the spindown age $P/2\dot{P} = 2000$ yr agrees with the estimated age of the surrounding SNR Kes 73, and the spindown is very uniform. The implied (polar) dipole field of 1.4×10^{15} G is a good candidate for the strongest yet measured in any neutron star.

However, the measured spindown ages of SGR 1806-20 and SGR 1900+14, $P/2\dot{P} = 1400$ yr (Kouveliotou et al. 1998, 1999; Marsden, Rothschild, & Lingenfelter 1999; Woods et al. 1999c) do not appear to obey a similar correspondence. Indeed, the characteristic age of SGR 1900+14 is surprisingly short if it has been spun down by a constant external torque, and if it is physically associated with the nearby SNR G42.8+0.6: the required proper motion is $V_\perp \simeq 20,000\,(D/7\text{ kpc})\,(t/1,500\text{ yr})^{-1}$ km s^{-1}. (A spurious association leads to an equally unsatisfactory situation: a very young neutron star bereft of a progenitor supernova.) This inconsistency disappears if the spindown of SGR 1900+14 is *temporarily accelerated* with respect to the long-term trend.

5.2. DEPARTURES FROM UNIFORM SPINDOWN

One of the defining characteristics of the AXPs is that they are consistently spinning down. Nonetheless, torque variations are evident in the sources 1E 2259+586, 1E 1048.1+5937, and 4U 0142+61 (Heyl & Hernquist 1999; Mereghetti et al. 2000). Over the longest intervals measured, the spin evolution of the AXPs is unusually coherent by the standards of accreting neutron stars. Dramatically improved timing accuracy has been achieved recently through phase-connected measurements (Kaspi et al. 1999), which show that the spindown of 1E 2259+586 and RXSJ170849-4009 is, also, remarkably smooth over an interval of $\sim 10^3$ days. Thus, variations in the spindown may occur only intermittently. Recent phase-connected measurements of the spindown of SGR 1806-20 (Woods et al. 2000) point to significantly stronger torque variations than are present in the AXPs 1E 2259+586 and RXSJ170849-4009, or are characteristic of radio pulsars.

Most intriguingly, the spindown of 1E 1048.1+5937 appears to have accelerated for a ~ 5 yr interval over the long term trend (Paul et al. 2000), a phenomenon that was inferred for SGR 1900+14 only indirectly from its spindown age. The main question which next arises, is whether this accelerated torque is comparable to that expected from an orthogonal vacuum rotator. If so, then in the case of SGR 1900+14 the polar dipole field is inferred to be $B_{dipole} \simeq 1 \times 10^{15}$ G. A temporary acceleration *up* to the standard dipole torque is the expected consequence of a recent discharge of particles through bursting activity, if the magnetic and rotational axes of the star are almost aligned. That is because in quiescence, the outer magnetosphere of the neutron star would become charge-starved at the measured 5.16-s spin period, with a corresponding reduction in the long-term torque (T00). Independent evidence for such a torque reduction is present in the AXP 1E 2259+586, whose spindown age of $\sim 2 \times 10^5$ yr significantly *exceeds* the estimated age of its host supernova remnant CTB 109.

Also intriguingly, the spin period of SGR 1900+14 increased by $\Delta P/P = +1 \times 10^{-4}$ above the long term trend within an 80-day interval surrounding the August 27 giant outburst (Woods et al. 1999c). A transient flow of particles, photons, and Alfvén waves might provide the additional torque – by increasing the magnetic field strength at the light cylinder and by carrying off angular momentum directly – but the constraint on B_{dipole} is severe (T00). The net effect of such a flow (Thompson & Blaes 1998) is to increase the spindown luminosity to the geometric mean of L_{Alfven} and the standard magnetic dipole luminosity, $I\Omega\dot{\Omega} = \Lambda\, B_{NS} R_{NS} (\Omega R_{NS}/c)^2\, (L_{Alfven} c)^{1/2}$. Subsequent calculations have found the numerical coefficient to be $\Lambda = \sqrt{2}/3$ (Harding et al. 1999) and $\Lambda = 2/3$ (T00). Applying this formula to the August 27 outburst, and normalizing the radiated energy and duration to the observed values ($\sim 10^{44}$ erg and ~ 100 s), one finds $\Delta P/P = 1 \times 10^{-5}\, (\Lambda/\frac{2}{3})\, (\Delta E/10^{44}\ \mathrm{erg})^{1/2}\, (\Delta t/100\ \mathrm{s})^{1/2}\, (B_{dipole}/10\, B_{QED})$. This falls below the measured value even for $B_{dipole} \sim 10\, B_{QED}$, but a more extended particle flow or an undetected soft X-ray component to the giant burst cannot be ruled out.

The long-term spindown rate of SGR 1900+14 appears not to have been perturbed by the August 27 event (Woods et al. 1999c). This observation has the important consequence that the active region of the neutron star must carry a small fraction of the external magnetic energy; hence one deduces a lower bound to the dipole field of $\sim 10\, B_{QED} = 4.4 \times 10^{14}$ G (T00).

It should be kept in mind that the measured spindown luminosity $I\Omega\dot{\Omega}$

of the AXPs and SGRs is typically two orders of magnitude smaller than the persistent X-ray luminosity. As the above formula makes clear, the spindown resulting from the the release of a fixed energy increases with the duty cycle, because at a lower flux the Alfvén radius (and the lever arm) is increased. The inferred dipole fields of the two spinning-down SGRs are reduced (by a factor of ~ 4) to 4×10^{14} G if the each star is a persistent source of Alfvén waves and particles with a luminosity comparable to $L_X \sim 10^{35}$ erg s^{-1} (Thompson & Blaes 1998; Kouveliotou et al. 1998, 1999; Harding, Contopoulos, & Kazanas 1999; T00). These values lie only a factor ~ 4 above the polar dipole field inferred for the new radio pulsar J1814-1744.

The evidence for a physical association between SGR 1806-20 and a conspicuous radio nebula (Kulkarni & Frail 1993; Vasisht et al. 1994) which originally motivated persistent particle winds from the SGRs has been called into question (Hurley et al. 1999d). In addition, the relatively constant long-term spindown rate of SGR 1900+14 (Woods et al. 1999c) indicates that transient surges in the persistent seismic output, if present in SGR 1900+14, must be constant over a long timescale. They do not appear to correlate directly with episodes of short outbursts.

Melatos (1999) has recently noted the intriguing possibility that the spindown torque coupled to the asymmetric inertia of the co-rotating magnetic field could be particularly effective at forcing precession in a magnetar. Free precession (which in this model is modulated by the spindown torque) has a period $\tau_{prec} = P/\varepsilon_B = 7\,(P/6\text{ s})\,(B_{core}/10^2 B_{QED})^{-2}$ day, where $\varepsilon_B \simeq 1 \times 10^{-5}(B_{core}/10^2 B_{QED})^2$ is the dimensionless quadrupole distortion of the star by the (toroidal core) magnetic field. This period is already rather short compared with the observed spindown variations, if the magnetic field is strong enough to power the observed X-ray emission. In addition, pinning of superfluid vortex lines in the neutron star crust will force the precession period down to $\tau_{prec} = P(I/I_{sf})$, where I_{sf} is the fraction of the moment of interia carried by the neutron superfluid (Shaham 1977). Detection of a spinup glitch in 1RXS J170849.0-4000910 provides direct evidence for sufficient pinning to suppress long-period precession (Kaspi, Lackey, & Chakrabarty 2000).

5.3. SUPERFLUIDITY AND GLITCHES

Superfluid-driven glitches are a potential source of spindown irregularities in isolated magnetars. SGRs 1900+14 and 1806-20 have frequency derivatives about one-tenth that of the Vela pulsar, and models of magnetic dissipation suggest internal temperatures that are comparable or higher (TD96; Heyl & Kulkarni 1998). A giant outburst like the August 27 event must involve a large fracture of the crust propagating at $\sim 10^8$ cm s^{-1}, which almost certainly unpins the $^1S_0$ neutron superfluid vortex lines from the crustal lattice. The maximum glitch that could result can be very crudely estimated (TD96) by assuming a characteristic maximum angular velocity difference $\Delta\Omega_{max}$ between the superfluid and lattice, and then scaling to the largest observed glitches (e.g. $\Delta P/P \sim -3 \times 10^{-6}$ in Vela). This gives $|\Delta\Omega/\Omega| \sim \Delta\Omega_{max}/\Omega \propto \Omega^{-1}$ and $|\Delta P/P| \simeq 3 \times 10^{-4}(P/8\ \mathrm{s})$.

In light of this, let us reconsider the observation of a transient spindown in SGR 1900+14 ($\Delta P/P = +1\times10^{-4}$) close to the August 27 giant outburst (Woods et al. 1999c). Could this be a superfluid-driven glitch in spite of the 'wrong' sign? The crust of a magnetar is deformed plastically by magnetic stresses wherever $B > (4\pi\mu)^{1/2} \sim 6 \times 10^{15}$ G (TD96). Such a deformation taking place on a timescale short compared to $P/\dot{P}$ will force the pinned vortex lines into an inhomogeneous distribution (with respect to cylindrical radius). The net effect is to *slow* the rotation of the superfluid with respect to the crust. A sudden unpinning event would then tend to *spin down* the rest of the star (T00).

Heyl and Hernquist (1999) estimated the glitch activity in a few variable AXPs, under the assumption that the spindown irregularities are entirely due to glitches of the same sign as pulsar glitches. However, recent phase-connected measurements of variable spindown in SGR 1806-20 do not support this hypothesis (Woods et al. 2000). For that reason, it is important to consider alternative mechanisms for spindown variations involving, e.g., acceleration of the torque by particle outflows from the active neutron star.

6. Persistent Emission of the SGRs and AXPs

The persistent X-ray output of the Soft Gamma Repeaters lies within a fairly narrow range of $1 - 10 \times 10^{35}$ erg/s, and has a characteristically hard spectrum with a power-law component $dN/dE \propto E^{-2}$ (Murakami et al. 1994; Hurley et al. 1999c; Woods et al. 1999b). The output of the AXPs is slightly broader but much softer spectrally, being well fit by a $\sim$ 0.5 keV blackbody plus a (soft) non-thermal tail with photon index $\sim 3-4$ (Mereghetti 2000, and references therein). Direct evidence that the persistent X-ray output of SGR 1900+14 is not powered by accretion comes from the detection of (enhanced) emission a day after the giant August 27 flare (Murakami et al. 1999; Woods et al. 1999c). Enough radiative momentum was deposited during that outburst to excavate any accretion disk out to a very large radius, within which accretion would be established only on a much longer timescale of months (T00).

The spectral characteristics of the SGRs and AXPs suggest that i) dissipation of magnetic energy in a neutron star can produce varying persistent X-ray spectra, with hardness correlating strongly with bursting activity;

and ii) that more than one mechanism can generate persistent X-ray emission at a level of $\sim 10^{35}$ erg s^{-1}. Four such mechanisms have been proposed, all of which can be expected to operate in an SGR and at least two of which are relevant to the AXPs. We summarize them in turn:

1. *Ambipolar diffusion of a magnetic field through the neutron star core, combined with the increased transparency of the stellar envelope in a strong magnetic field* (TD96; Heyl & Kulkarni 1998). The degenerate charged electrons and protons are tied to the magnetic field lines in the neutron star core. They can be dragged across the background neutron fluid, but only very slowly (Pethick 1992; Goldreich & Reisenegger 1992). Heating of the core feeds back strongly on the rate of ambipolar diffusion (TD96). An intense magnetic field drives an imbalance between the chemical potentials of the electrons, protons and neutrons, $\Delta\mu = \mu_e + \mu_p - \mu_n \simeq B^2/8\pi n_e$, and this imbalance induces β-reactions which heat the core. Above a critical flux density, the heat produced exceeds the heat remaining in the star from its formation, and the core sits at an equilibrium temperature where heating is balanced by neutrino cooling. In practice, this balance is possible only as long as the neutrino emissivity is dominated by the modified-URCA reactions. The very strong temperature-dependence of these reactions translates into a very strong B-dependence of the diffusion rate: $t_{amb} = 10^4\ (B_{core}/7 \times 10^{15}\ \mathrm{G})^{-14}$ yr in a normal n-p-e plasma (TD96). (This timescale depends, of course, on the *core* flux density.) Assuming a magnetized iron envelope, the resulting heat flux through the surface is $L_X(t) = 5 \times 10^{34}\ (t/10^4\ \mathrm{yr})^{-0.3}$ erg s^{-1}. Thus, there is a critical flux density above which magnetic dissipation is rapid, but below which the magnetic field is essentially frozen. *This critical flux density exceeds by a factor* $\sim 4 - 10$ *the dipole fields that are inferred from SGR and AXP spindown.* The absence of significant X-ray emission from the pulsar PSR J1814-1744 (Pivovaroff et al. 2000) (with a polar dipole field $\sim 10^{14}$ G) is consistent with the magnetar hypothesis as long as the internal (e.g. toroidal) field in these objects is below the critical value.

Further time-dependent calculations of ambipolar diffusion through normal n-p-e nuclear matter, including much more detailed modelling of the envelope, are reported by Heyl & Kulkarni (1998). Calculations of heat transport through the strongly magnetized envelope of a neutron star are presented in Hernquist (1985), Van Riper (1988), Potekhin & Yakovlev (1996) and Heyl & Hernquist (1998).

2. *Hall fracturing in the crust* (TD96). Protons are bound into a rigid Coulomb lattice of nuclei in the neutron star crust. In this situation, the propagation of short-wavelength magnetic irregularities through the crust is driven by the Hall electric field $\vec{E} = \vec{J} \times \vec{B}/n_e ec = (\vec{\nabla} \times \vec{B}) \times \vec{B}/4\pi n_e e$ (Goldreich & Reisenegger 1992). The polarization of a such a Hall wave rotates, which causes the crust to *yield or fracture* in a magnetic field stronger than $\sim 10^{14}$ G. A significant fraction of the wave energy is dissipated in this manner – in less than the age t_{NS} of the neutron star – if the turbulence has a short wavelength $\lambda < 0.1\,(\delta B/B)^{-1/2}(\theta_{max}/10^{-3})^{1/2}$ $(B^2/4\pi\mu)^{-1/4}\,(t_{NS}/10^4\ \mathrm{yr})^{1/2}$ km (TD96). (Recall that $(4\pi\mu)^{1/2} = 6\times 10^{15}$ G in the deep crust.) By contract, large-scale fractures which are capable of triggering giant outbursts require more rapid transport of the magnetic field, which can occur via ambipolar diffusion through the *core*.

Each Hall fracture releases only a small energy, $\Delta E \sim 10^{36}\,(\theta_{max}/10^{-3})^{7/2}$ erg. The cumulative effect is to excite persistent seismic activity with a net output $L_{seismic} \sim 10^{35}\,(\delta B/B)^2\,(B/10^{15}\ \mathrm{G})^2\ (t_{NS}/10^4\ \mathrm{yr})^{-1}$ erg s^{-1}. The excited seismic waves have a frequency $\nu \sim c_\mu/\lambda \sim 10^4$ Hz, where $c_\mu \sim c/300$ is the shear wave speed in the deep crust. These internal waves couple to transverse (Alfvén) excitations of the magnetosphere at a radius $R_\nu \sim c/3\nu \sim 100\,\lambda$. Only a fraction of the wave energy need be converted to particles to support the associated electrical currents (Thompson & Blaes 1998).

3. *Twisting of the external magnetic field lines by internal motions of the star, which drives persistent electrical currents through the magnetosphere* (T00). The persistent light curve of SGR 1900+14 underwent a dramatic change following the August 27 outburst (Murakami et al. 1999): it brightened by a factor ~ 2.5 and at the same time simplified dramatically into a single large pulse. This change appeared within a day following the August 27 event, indicating that the source of the excess emission involves particle flows *external* to the star (T00). The coordinated rise and fall of the two X-ray pulses of 1E 2259+586 over a period of a few years detected by Ginga (Iwasawa, Koyama, & Halpern 1992) similarly indicates that some portion of its emission is magnetospheric (TD96).

The rate of dissipation due to a twisting of a bundle of field lines (of flux density B, radius a, twist angle θ and length L) can be estimated as follows (T00). The associated charge flow is $\dot{N} \sim \theta B a^2 c/8L$ into the magnetosphere from either end of the twisted field. The surfaces of the SGRs and AXPs are hot enough to emit thermionically for a wide range of surface compositions – even in the presence of $\sim 10^{15}$ G magnetic fields – and so the space charge very nearly cancels. An electric field $\vec{E}\cdot\vec{B} = -(Am_p/Ze)\vec{g}\cdot\vec{B}$ will compensate the gravitational force on the ions; but the same field pushes the counterstreaming electrons to bulk relativistic motion. The net luminosity in Comptonized X-ray photons is $L_{Comp} \sim 3\times 10^{35}\theta(A/Z)(B/10\,B_{QED})\,(L/R_{NS})^{-1}\,(a/0.5\ R_{NS})^2$ erg s^{-1}. This agrees with the measured value if a few percent of the crust is involved in the August 27 outburst. (Independent evidence for an active fraction this size comes from the unperturbed long-term spindown of SGR 1900+14, and from the expectation of $\sim 10^2$ giant outbursts per SGR in $\sim 10^4$ yr.) This non-thermal energy source will decay in 10-100 years, and so provides a physical motivation for *non-thermal* persistent X-ray spectra in *active* burst sources. (Note that the measured increase in the persistent L_X of SGR 1900+14 came entirely in the non-thermal component of the spectrum: Woods et al. 1999a.)

4. Heyl and Hernquist (1997a,b) have explored the interesting possibility that the emission of some AXPs is predominantly due to *passive surface cooling, possibly enhanced by a light H or He composition.* This model is most promising for the AXP 1E 1841-045, but cannot directly accomodate the variable L_X of 1E 2259+586 or 1E 1048.1+5937. A challenge for this model comes from the very similar spin periods and persistent X-ray luminosities of the active SGRs and the quiescent AXPs. The magnetic dissipation occuring within an active SGR lengthens its *lifetime* as an bright X-ray source (TD96; Heyl & Kulkarni 1998).

6.1. RADIO EMISSION FROM MAGNETARS

The upper cutoff to the measured distribution of pulsar dipole fields lies close to B_{QED}. It is natural to ask whether this apparent cutoff results from observational selection or, instead, reflects a more fundamental physical limitation on pair cascades in very strong magnetic fields. As emphasized by Camilo et al. (2000), the discovery of three new strong-field pulsars allows for a substantial population of these objects.

The most salient point, I believe, is that *particle flows induced by bursting activity* could short out vacuum gaps in the magnetospheres of the SGRs. The hyper-Eddington outbursts can easily blow material off the stellar surface (TD95; Miller 1995; Ibrahim et al. 2000). A modest amount of material will remain centrifugally supported outside the corotation radius (where the Keplerian orbital period equals the spin period of the star, $R_{co} = 6 \times 10^8\,(P/6\text{ s})^{2/3}$ cm) and still be confined by the dipole magnetic field: $\Delta M \sim (B_{NS}^2/4\pi)\Omega^{4/3}R_{NS}^6\,(GM_{NS})^{-5/3} = 3{\times}10^{20}(B_{NS}/10\,B_{QED})^2\,(P/6\,\text{s})^{-4/3}$ g. After an X-ray outburst, this material cools and settles into a rotationally supported disk, which spreads outward adiabiatically as the centrifugal force density rises above $B^2/4\pi$ at the co-rotation radius. By spreading out to the speed-of-light cylinder, this material can maintain a relativistic flux of particles at the Goldreich-Julian density $n_{GJ} = \Omega \cdot B/2\pi ec$ for as long as $\sim 1 \times 10^5\,(B_{NS}/10\,B_{QED})\,(P/6\text{ s})^{2/3}$ yr. Above this density, particles flowing downward toward the star from the light cylinder would short out the 'favorably curved' magnetic field lines that otherwise support a relativistic thermionic flow from the surface of the neutron star (e.g. Scharlemann et al. 1978). If this is happening in the SGRs, radio emission may be easier to detect from the quiescent AXPs.

Alternatively, it has been suggested that pair cascades (and thence coherent radio emission) are *directly* suppressed in isolated strong-field neutron stars through QED effects: either by conversion of gamma-rays to bound positronium rather than to free pairs (Usov & Melrose 1996); or by photon splitting below the threshold for pair creation, $\gamma \rightarrow \gamma + \gamma$ (Baring & Harding 1998). Regarding the first mechanism, it should be emphasized that one polarization mode – the E-mode – converts to positronium with one particle in an excited Landau state. The energy released through the subsequent decay greatly exceeds the binding energy of the pair, which suggests that an unbound pair results. Notice also that the SGRs and AXPs emit a large enough flux of soft X-rays ($L_X \sim 3 \times 10^{34} - 10^{36}$ erg s^{-1}) to photo-dissociate bound positronium (cf. Usov & Melrose 1996). The other mechanism for suppressing radio emission just discussed is based on a doubtful assumption that both polarization modes can split below the threshold for single-photon pair creation (see §4.5). More generally, the splitting rate drops off so rapidly with distance from the neutron star ($\propto B^6 \sim R^{-18}$ when $B < B_{QED}$) that the region outside the 'splitting photosphere' should sustain a sufficient potential drop to induce pair cascades when the spin period lies well below the conventional radio death line. In other words, splitting will probably induce additional curvature in the pulsar death line at $B > B_{QED}$, but not suppress radio emission at much shorter spin periods.

7. Origins of Neutron Star Magnetism

The idea of magnetars was motivated by the realization that the violent convective motions in a collapsing supernova core can strongly amplify the entrained magnetic field (Thompson & Duncan 1993, hereafter TD93). The intense flux of neutrinos drives convection both in the central part of the core that is very thick to neutrino scattering and absorption (Pons et al. 1999, and references therein) and in a thin mass shell below the bounce shock where neutrino heating overcomes cooling (Janka & Mueller 1996, and references therein). Balancing hydrodynamic and magnetic stresses, one deduces magnetic fields of $\sim 10^{15}$ G and $\sim 10^{14}$ G respectively (TD93; Thompson 2000a). The convection inside the neutrinosphere has an overturn time τ_{con} of a few milliseconds; the overturn time in the outer 'gain' region is somewhat longer. The inner region will support a large-scale helical dynamo if the core is very rapidly rotating, with $P_{rot} < \tau_{con}$ (DT92), but not otherwise. It is also possible that rapid rotation by itself could amplify a magnetic field (Leblanc & Wilson 1970) through the magnetic shearing instability (Balbus & Hawley 1991) in the absence of convection, if the outermost parts of the collapsing core became centrifugally supported.

A newborn neutron star experiences convection with a dimensionless ratio of convective kinetic energy to gravitational binding energy ($\varepsilon_{con} \sim 10^{-4}$) that is some two orders of magnitude larger than in any previous phase driven by nuclear burning (TD93). (This is the relevant figure of merit because the gravitational binding energy and the magnetic energy are proportional under an expansion or contraction.) For this reason, neutron star magnetic fields are probably not fossils from earlier stages of stellar evolution. The intense flux of neutrinos emanating from the neutron core induces rapid heating and $n - p$ transformations, thereby allowing magnetic fields stronger than $\sim 10^{14}$ G to rise buoyantly through a thick layer of convectively stable material in less than the Kelvin time of ~ 30 s (Thompson & Murray 2000). As a result, the $10^{11} - 10^{13}$ G magnetic moments of ordinary radio pulsars, which do not appear to correlate with the axis of rotation, have a plausible origin (TD93) in a stochastic dynamo operating at slow rotation ($P_{rot} \gg \tau_{con}$). Direct amplification of a magnetic field $\langle B^2 \rangle^{1/2}$ within individual convective cells of size $\ell \sim (\frac{1}{30} - \frac{1}{10})\, R_{NS}$ will generate a true dipole of magnitude $B_{dipole} \sim \langle B^2 \rangle^{1/2} (\ell^2/4\pi R_{NS}^2)^{1/2} \sim 10^{13}$ G through an incoherent superposition. A similar effect can occur during fallback as convection develops below the accretion shock (Thompson & Murray 2000).

7.1. LARGE KICKS

There is evidence that some (but not all) SGRs have proper motions approaching ~ 1000 km s^{-1}. The quiescent X-ray source associated with SGR 0526-66 (the March 5 burster) is offset from the center of N49, implying $V_\perp \sim 800\,(t/10^4 \text{ yr})^{-1}$ km s^{-1} perpendicular to the line-of-sight (DT92). Similarly, the association of SGR 1900+14 with G42.8+0.6, if real, implies $V_\perp \sim 3000\,(t/10^4 \text{ yr})^{-1}$. Additional indirect evidence that magnetars tend to have received large kicks comes from the paucity of accreting, strong-B neutron stars. However, it should be emphasized that the proper motions of SGR 1806-20 may be as small as ~ 100 km s^{-1}, and that the projected positions of the AXPs 1E 2259+586 and 1E 1841-045 are close to the centers of their respective remnants.

Since the SGRs already appear to have one unusal property (very strong magnetic fields), one immediately asks if a large kick could be produced by a mechanism that does not operate, or operates inefficiently, in ordinary proto-pulsars. Two mechanisms are particularly attractive if the star is initially a rapid rotator (DT92; Khokhlov et al. 1999; Thompson 2000a): anisotropy in the emission of the cooling neutrinos caused by large scale magnetic spots, which suppress convective transport within the star; and asymmetric jets driven by late infall of centrifugally supported material. The first model is supported by observations of rotating M-dwarfs, which have deep convective zones (like proto-neutron stars) and develop large, long-lived polar magnetic spots: Vogt 1988). One estimates $M_{NS}V_{NS} \sim (E_\nu/c)\,(\tau_{spot}/\tau_{KH})^{1/2}\,(\Delta\Omega_{spot}/4\pi)$, where τ_{spot} is the coherence time of the spot(s) and τ_{KH} the Kelvin time of the star. The corresponding magnetic dipole field is $B_{dipole} \sim 5 \times 10^{14}\,(V_{NS}/1000 \text{ km s}^{-1})\,(\tau_{spot}/\tau_{KH})^{-1/2}$ G. Note that this refers to the dipole field in the *convective* neutron core, and represents an upper bound to the remnant field generated by an internal dynamo.

An asymmetric jet provides a more efficient source of linear momentum than does radiation from an off-center magnetic dipole (Harrison & Tademaru 1975), for two reasons: 1) The jet is matter-loaded and the escape speed from a proto-neutron star of radius ~ 30 km is only $\sim \frac{1}{4}$ the speed of light; and 2) a centrifigually supported disk carrying the same amount of angular momentum $(GM_{core}R_{core})^{1/2}\Delta M$ as a hydrostatically supported neutron core can provide much more energy to a directed outflow. The respective energies are $\Delta E \sim GM_{core}\Delta M/2R_{core} = 6 \times 10^{50}(\Delta M/10^{-2}\,M_\odot)\,(R_{core}/30 \text{ km})^{-1}$ erg and $\Delta E \sim \frac{5}{4}G(\Delta M)^2/R_{core} = 10^{48}\,(\Delta M/10^{-2}\,M_\odot)^2\,(R_{core}/30 \text{ km})^{-1}$ erg for a $1.4\,M_\odot$ core. The corresponding kick velocity is $\sim 300\,f\,(\Delta M/10^{-2}\,M_\odot)\,(R_{core}/30 \text{ km})^{-1/2}$ km s^{-1}, where f is the fractional asymmetry in the momentum. Only a very energetic jet ($\Delta E \sim 6 \times 10^{51}\,(f/0.3)^{-1}$ erg) can generate a kick of 1000 km s^{-1}.

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